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# ON A WEIGHTED GENERALIZATION OF IYENGAR TYPE INEQUALITIES INVOLVING BOUNDED FIRST DERIVATIVE

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ABSTRACT. Inequalities are obtained for weighted integrals in terms of bounds involving the first derivative of the function. Quadrature rules are obtained and the classical Iyengar inequality for the trapezoidal rule is recaptured as a special case when the weight function  $w(x) \equiv 1$ . Applications to numerical integration are demonstrated.

## 1. INTRODUCTION

In 1938, Iyengar proved the following theorem obtaining bounds for a trapezoidal quadrature rule for functions whose derivative  $|f'(x)| < M$  for  $x \in (a, b)$  (see for example [3, p. 471]).

**Theorem 1.** *Let  $f$  be a differentiable function on  $(a, b)$  and assume that there is a constant  $M > 0$  such that  $|f'(x)| \leq M, \forall x \in (a, b)$ . Then we have*

$$(1.1) \quad \left| \int_b^a f(x) dx - (b-a) \frac{f(a) + f(b)}{2} \right| \leq \frac{M(b-a)^2}{4} - \frac{1}{4M} (f(b) - f(a))^2.$$

Using a classical inequality due to Hayashi (see, [2, pp. 311-312]), Agarwal and Dragomir proved in [1] the following generalization of Theorem 1.

**Theorem 2.** *Let  $f : I \subseteq \mathbb{R} \rightarrow \mathbb{R}$  be a differentiable mapping on  $\overset{\circ}{I}$ , the interior of  $I$ , and let  $a, b \in \overset{\circ}{I}$  with  $a < b$ . Let  $M = \sup_{x \in [a, b]} f'(x) < \infty$  and  $m = \inf_{x \in [a, b]} f'(x) > -\infty$ . If  $m < M$  and  $f'$  is integrable on  $[a, b]$ , then we have*

$$(1.2) \quad \begin{aligned} & \left| \int_a^b f(t) dt - (b-a) \frac{f(a) + f(b)}{2} \right| \\ & \leq \frac{[f(b) - f(a) - m(b-a)][M(b-a) - f(b) + f(a)]}{2(M-m)}. \end{aligned}$$

Thus, substituting  $m = -M$  in (1.2) reproduces Iyengar's result (1.1).

Cerone and Dragomir [6] produced a number of generalizations of the above results and in particular, they obtained a non-symmetric inequality for a generalized trapezoidal quadrature rule. The following theorem is proved by Cerone and Dragomir [6].

**Theorem 3.** *Let  $f : I \subseteq \mathbb{R} \rightarrow \mathbb{R}$  be a differentiable mapping on  $\overset{\circ}{I}$  (the interior of  $I$ ) and  $[a, b] \subset \overset{\circ}{I}$  with  $M = \sup_{x \in [a, b]} f'(x) < \infty$ ,  $m = \inf_{x \in [a, b]} f'(x) > -\infty$  and*

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$M > m$ . If  $f'$  is integrable on  $[a, b]$ , then the following inequality holds:

$$(1.3) \quad \beta_L \leq \int_a^b f(x) dx - [(\theta - a)f(a) + (b - \theta)f(b)] \leq \beta_U$$

where

$$\beta_U = \frac{(b-a)^2}{2(M-m)} [S(2\gamma_U - S) - mM],$$

$$\beta_L = \frac{(b-a)^2}{2(M-m)} [S(S - 2\gamma_L) + mM]$$

with

$$\gamma_U = \left(\frac{\theta - a}{b - a}\right)M + \left(\frac{b - \theta}{b - a}\right)m, \quad \gamma_L = M + m - \gamma_U,$$

and

$$S = \frac{f(b) - f(a)}{b - a}.$$

Taking  $\theta = \frac{a+b}{2}$  in (1.3) will reproduce the result of Agarwal and Dragomir [1], (1.2). In addition, if  $m = -M$  then (1.1) of Iyengar's is obtained.

In the current article a trapezoidal type rule is obtained for the weighted integral  $\int_a^b w(x)f(x)dx$  and thus may be looked upon as a generalization of the Agarwal and Dragomir [1] result. Placing  $m = -M$  gives a generalization of the Iyengar result (1.1) for weighted integrals.

## 2. PRELIMINARIES

Some definitions are required to simplify the subsequent work.

**Definition 1.** Let  $w(x)$  be a positive integrable function on  $[a, b]$ . Let  $\nu$  be its zeroth moment about zero so that

$$(2.1) \quad \nu = \int_a^b xw(x)dx < \infty.$$

**Definition 2.**  $P$  and  $Q$  will be used to denote the zeroth and first moments of  $w(x)$  over a subinterval of  $[a, b]$ . In particular, for  $\lambda > 0$  the subscript  $a$  or  $b$  will be used to indicate the intervals  $[a, a + \lambda]$  and  $[b - \lambda, b]$  respectively. Thus, for example,

$$P_a = \int_a^{a+\lambda} w(x)dx$$

and

$$Q_b = \int_{b-\lambda}^b xw(x)dx.$$

The following theorem is due to Hayashi (see for example [2, pp. 311-312]).

**Theorem 4.** Let  $h : [a, b] \rightarrow \mathbb{R}$  be a nonincreasing mapping on  $[a, b]$  and  $g : [a, b] \rightarrow \mathbb{R}$  an integrable mapping on  $[a, b]$  with

$$0 \leq g(x) \leq A, \text{ for all } x \in [a, b].$$

Then

$$(2.2) \quad A \int_{b-\lambda}^b h(x) dx \leq \int_a^b h(x) g(x) dx \leq A \int_a^{a+\lambda} h(x) dx$$

where

$$\lambda = \frac{1}{A} \int_a^b g(x) dx.$$

Hayashi's inequality (2.2) will now be used to obtain inequalities for weighted integrals to give trapezoidal type quadrature rules.

### 3. TRAPEZOIDAL INEQUALITY FOR WEIGHTED INTEGRALS

An inequality for weighted integrals will now be developed for a trapezoidal rule, but firstly, two lemmas will need to be proved by the use of the Hayashi inequality.

**Lemma 1.** *Let  $f : I \subseteq \mathbb{R} \rightarrow \mathbb{R}$  be a differentiable mapping on  $\overset{\circ}{I}$  (the interior of  $I$ ) and  $[a, b] \subset \overset{\circ}{I}$  with  $M = \sup_{x \in [a, b]} f'(x) < \infty$ ,  $m = \inf_{x \in [a, b]} f'(x) > -\infty$  and  $M > m$ . Let  $w(x) \geq 0$  for all  $x \in [a, b]$  and  $\nu = \int_a^b xw(x) dx < \infty$  be the first moment of  $w(\cdot)$  on  $[a, b]$ . If  $f'$  is integrable on  $[a, b]$  then the following inequality holds:*

$$(3.1) \quad \begin{aligned} & (M - m) [Q_b - (b - \lambda) P_b] \\ & \leq \int_a^b w(x) f(x) dx - \nu (f(a) - ma) - \frac{m}{2} (b^2 - a^2) \\ & \leq (M - m) [Q_a - (\lambda + a) P_a + \lambda \nu] \end{aligned}$$

where  $P, Q$  are as described in Definition 2 and  $\lambda = \frac{b-a}{M-m} (S - m)$ ,  $S = \frac{f(b)-f(a)}{b-a}$ .

*Proof.* Let  $h_b(x) = \int_x^b w(u) du$  and  $g(x) = f'(x) - m$ . Then from Hayashi's inequality (2.2)

$$(3.2) \quad L_b \leq I_b \leq U_b$$

where

$$I_b = \int_a^b h_b(x) (f'(x) - m) dx,$$

$$\lambda = \frac{1}{M - m} \int_a^b (f'(x) - m) dx,$$

and

$$L_b = (M - m) \int_{b-\lambda}^b h_b(x) dx,$$

$$U_b = (M - m) \int_a^{a+\lambda} h_b(x) dx.$$

Now, an integration by parts gives

$$(3.3) \quad I_b = -\nu (f(a) - ma) - \frac{m}{2} (b^2 - a^2) + \int_a^b w(x) f(x) dx.$$

Also,

$$(3.4) \quad \lambda = \frac{b-a}{M-m} (S-m)$$

where

$$S = \frac{f(b) - f(a)}{b-a},$$

the slope of the secant over  $[a, b]$ .

It should be noted that  $0 < \lambda \leq b-a$  since  $S \leq M$ .

For the lower bound  $L_b$  a change of order of integration gives

$$(3.5) \quad \begin{aligned} \frac{L_b}{M-m} &= \int_{b-\lambda}^b w(x) \int_{b-\lambda}^u dx du \\ &= (\lambda-b) P_b + Q_b \end{aligned}$$

where  $P_b$  and  $Q_b$  are as described in Definition 2.

Similarly, the upper bound  $U_b$  may be obtained through a change of order of integration to give

$$(3.6) \quad \begin{aligned} \frac{U_b}{M-m} &= \int_a^{a+\lambda} w(u) \int_a^u dx du + \int_{a+\lambda}^b w(u) \int_a^{a+\lambda} dx du \\ &= \int_a^{a+\lambda} (u-a) w(u) du + \lambda \int_{a+\lambda}^b w(u) du \\ &= Q_a - (\lambda+a) P_a + \lambda \nu \end{aligned}$$

where  $P_a$  and  $Q_a$  are as described in Definition 2 and  $\nu$  is the zeroth moment of  $w(x)$  on  $[a, b]$ .

Using (3.2) – (3.6) the lemma is thus proved. ■

**Lemma 2.** *Let the conditions be as in Lemma 1 then the following inequality holds:*

$$(3.7) \quad \begin{aligned} &(M-m) [Q_b - (\lambda-b) P_b - \lambda \nu] \\ &\leq \int_a^b w(x) f(x) dx - \nu (f(b) - mb) - \frac{m}{2} (b^2 - a^2) \\ &\leq (M-m) [Q_a - (\lambda+a) P_a]. \end{aligned}$$

*Proof.* The proof follows along similar lines to that of Lemma 1.

Let  $h_a(x) = -\int_a^x w(u) du$  and  $g(x) = f'(x) - m$ . Then using Hayashi's inequality (2.2) gives:

$$(3.8) \quad L_a \leq I_a \leq U_a$$

where

$$I_a = \int_a^b h_a(x) (f'(x) - m) dx$$

and

$$L_a = (M-m) \int_{b-\lambda}^b h_a(x) dx,$$

$$U_a = (M-m) \int_a^{a+\lambda} h_a(x) dx.$$

Now, a straight forward integration by parts yields

$$(3.9) \quad I_a = -\nu(f(b) - mb) - \frac{m}{2}(b^2 - a^2) + \int_a^b w(x)f(x) dx.$$

Further, an interchange of the order of integration and simplification of results yields

$$(3.10) \quad \frac{L_a}{M-m} = Q_b + (\lambda - b)P_b - \lambda\nu$$

and

$$(3.11) \quad \frac{U_a}{M-m} = Q_a - (\lambda + a)P_a.$$

Hence, using (3.8) – (3.11) the lemma is proved. ■

**Theorem 5.** *Let the conditions of Lemmas 1 and 2 be maintained. Then the following inequality holds:*

$$(3.12) \quad \begin{aligned} & (M-m) \left[ Q_b - (b-\lambda)P_b - \frac{\lambda}{2}\nu \right] \\ & \leq \int_a^b w(x)f(x) dx - \frac{\nu}{2}[f(a) + f(b)] - m \left( \frac{a+b}{2} \right) (b-a-\nu) \\ & \leq (M-m) \left[ Q_a - (\lambda+a)P_a + \frac{\lambda}{2}\nu \right] \end{aligned}$$

where the  $P$ 's and  $Q$ 's are as defined in Definition 2.

*Proof.* Addition of (3.1) and (3.7) produces (3.12) upon division by 2. ■

**Corollary 1.** *Let the conditions be as in the previous Lemmas and theorems of this section. Then,*

$$(3.13) \quad \begin{aligned} & \left| \int_a^b w(x)f(x) dx - \frac{\nu}{2}[f(a) + f(b)] - m \left( \frac{a+b}{2} \right) [b-a-\nu] \right| \\ & \leq \frac{\nu}{2}(b-a)(S-m) \\ & \leq \frac{M-m}{2}\nu(b-a) \end{aligned}$$

where  $S$  is the slope of the secant on  $[a, b]$ .

*Proof.* The corollary follows readily from (3.12) on noting that

$$\begin{aligned} Q_b &= \int_{b-\lambda}^b xw(x) dx \geq (b-\lambda) \int_{b-\lambda}^b w(x) dx, \\ Q_a &= \int_a^{a+\lambda} xw(x) dx \leq (\lambda+a) \int_a^{a+\lambda} w(x) dx \end{aligned}$$

and substituting  $(M-m)\lambda = (b-a)(S-m)$ . ■

**Remark 1.** *Allowing  $w(x) \equiv 1$  in (3.12) gives from Definitions 1 and 2*

$$\nu = b-a, P_a = P_b = \lambda, Q_a = \frac{\lambda}{2}(\lambda+2a) \text{ and } Q_b = \frac{\lambda}{2}(2b-\lambda).$$

*This reveals the lower bound to be negative the upper bound and the result of Cerone and Dragomir [6] for the unweighted trapezoidal rule is recovered after some algebra.*

**Remark 2.** If  $w(x) \equiv 1$  in (3.13) then the coarser upper bound is obtained for the unweighted trapezoidal rule (1.2) since  $\frac{M-S}{M-m} < 1$ .

**Remark 3.** The bounds in (3.12) are not symmetric in general since for this to be so they must sum to zero. Let  $L_1$  be the lower bound and  $U_1$  be the upper bound. Then

$$U_1 + L_1 = (M - m) [(Q_b - (b - \lambda) P_b) - ((\lambda + a) P_a - Q_a)].$$

We know from the proof of Corollary 1 that  $Q_b \geq (b - \lambda) P_b$  and  $Q_a \leq (\lambda + a) P_a$ , so  $U_1 + L_1 = 0$  when  $Q_b - (b - \lambda) P_b = (\lambda + a) P_a - Q_a$ .

**Lemma 3.** Let the conditions of Theorem 3 and Lemmas 1 and 2 hold. Then, for  $w(x)$  symmetric about the mid-point  $\frac{a+b}{2}$ , the bounds in (3.12) are symmetric. Hence,

$$(3.14) \quad \left| \int_a^b w(x) f(x) dx - \frac{\nu}{2} [f(a) + f(b)] - m \left( \frac{a+b}{2} \right) [b-a-\nu] \right| \\ \leq (M-m) \left[ \frac{\lambda}{2} \nu - \int_0^\lambda uw(\lambda+a-u) du \right].$$

*Proof.* From Remark 3 and Definition 2, the sum of the upper and lower bounds in (3.12),  $U_1$  and  $L_1$  respectively is:

$$U_1 + L_1 = (M-m) \left[ \int_{b-\lambda}^b [x - (b-\lambda)] w(x) dx - \int_a^{a+\lambda} (\lambda+a-x) w(x) dx \right] \\ = (M-m) \left[ \int_0^\lambda uw(b-\lambda+u) du - \int_0^\lambda uw(\lambda+a-u) du \right].$$

Now,

$$U_1 + L_1 = (M-m) \int_0^\lambda u \left[ w\left(\frac{a+b}{2} + z\right) - w\left(\frac{a+b}{2} - z\right) \right] du$$

where  $z = \frac{b-a}{2} - \lambda + u$ .

Thus,

$$U_1 + L_1 \\ = (M-m) \int_{\frac{b-a}{2}-\lambda}^{\frac{b-a}{2}} \left( z + \lambda - \frac{b-a}{2} \right) \left[ w\left(\frac{a+b}{2} + z\right) - w\left(\frac{a+b}{2} - z\right) \right] dz \\ = 0$$

for  $w(\cdot)$  symmetric about  $\frac{a+b}{2}$ . Hence, the bounds in (3.12) are symmetric.

Now, from the upper bound in (3.12),  $U_1$  is such that:

$$\frac{U_1}{M-m} = \frac{\lambda}{2} \nu - [(\lambda+a) P_a - Q_a] \\ = \frac{\lambda}{2} \nu - \int_a^{a+\lambda} (\lambda+a-x) w(x) dx \\ = \frac{\lambda}{2} \nu - \int_0^\lambda uw(\lambda+a-u) du.$$

Thus, the lemma is proved. ■

It should be noted that the expression for  $U_1$  obtained above may be written as

$$\begin{aligned} \frac{U_1}{M-m} &= \frac{\lambda}{2}\nu - \int_0^\lambda uw \left( \frac{a+b}{2} - z \right) dz \\ &= \frac{\lambda}{2}\nu - \int_0^\lambda uw \left( z - \frac{a+b}{2} \right) dz \end{aligned}$$

where  $z = u + \frac{b-a}{2} - \lambda$ . Here, we are using the fact that the weight function  $w(\cdot)$  is symmetric about the mid-point.

**Corollary 2.** *Let the conditions be as in the previous lemmas and theorems of this section. Then*

$$\begin{aligned} (3.15) \quad & (M-m)[Q_b - (b-\lambda)P_b] - \nu \left[ \frac{b-a}{2}S + am \right] \\ & \leq \int_a^b w(x)f(x)dx - \frac{\nu}{2}[f(a) + f(b)] \\ & \leq (M-m)[Q_a - (\lambda+a)P_a] + \nu \left[ \left( \frac{b-a}{2} \right) S - bm \right] \\ & \quad + \frac{m}{2}(b^2 - a^2). \end{aligned}$$

*Proof.* A simple rearrangement of the terms in (3.12), collecting the coefficient of  $\nu$  and using the fact that  $(M-m)\lambda = (b-a)(S-m)$  produces the result. ■

**Remark 4.** *Using similar approximations as those in Corollary 1, simpler bounds may be obtained viz.,*

$$\begin{aligned} (3.16) \quad & \frac{m}{2}(b^2 - a^2) - \nu \left[ \left( \frac{b-a}{2} \right) S + am \right] \\ & \leq \int_a^b w(x)f(x)dx - \frac{\nu}{2}[f(a) + f(b)] \\ & \leq \frac{m}{2}(b^2 - a^2) + \nu \left[ \left( \frac{b-a}{2} \right) S - bm \right]. \end{aligned}$$

**Remark 5.** *There is no real advantage in using rule (3.15) in preference to (3.12) in practice since an adjustment factor involving only the end points for the  $\frac{m}{2}(b^2 - a^2)$  term and a simple sum reflecting the effect of the  $\frac{m}{2}(b+a)\nu$  term. This will be discussed further in Section 4.*

#### 4. APPLICATION IN NUMERICAL INTEGRATION

In this section we will demonstrate how the results obtained in Section 3 may be utilized to obtain quadrature rules for weighted functions.

**Theorem 6.** *Let  $f : [a, b] \rightarrow \mathbb{R}$  be a differentiable mapping on  $(a, b)$  with  $M = \sup_{x \in [a, b]} f'(x) < \infty$ ,  $m = \inf_{x \in [a, b]} f'(x) > -\infty$  and  $M > m$ . Let  $I_n$  be a partition of  $[a, b]$  such that  $I_n : a = x_0 < x_1 < \dots < x_{n-1} < x_n = b$ . Further, let  $w(x) \geq 0$  for all  $x \in [a, b]$  and  $\nu = \int_a^b w(x)dx < \infty$  be the first moment of  $w(\cdot)$  on  $[a, b]$ . Then, the following weighted quadrature rule holds*

$$\int_a^b w(x)f(x)dx = A(w, f, I_n) + R(w, f, I_n)$$



where  $A(w, f, I_n)$  is an approximation to the weighted integral. Namely,

$$\begin{aligned} A(w, f, I_n) &= \frac{1}{2} \sum_{i=0}^{n-1} \nu_i [f(x_i) + f(x_{i+1}) - m(x_i + x_{i+1})] + \frac{m}{2} (b^2 - a^2) \\ &= \frac{1}{2} \left[ \nu_0 g_0 + \nu_{n-1} g_n + \sum_{i=1}^{n-1} (\nu_{i-1} + \nu_i) g_i \right] + \frac{m}{2} (b^2 - a^2) \end{aligned}$$

with  $g_i = f(x_i) - mx_i$ .

In addition, the remainder term  $R(w, f, I_n)$  satisfies

$$\begin{aligned} |R(w, f, I_n)| &\leq \frac{1}{2} \sum_{i=0}^{n-1} \nu_i [f(x_{i+1}) - f(x_i) - m(x_{i+1} - x_i)] \\ &= \frac{1}{2} \left[ \nu_{n-1} g_n - \nu_0 g_0 + \sum_{i=1}^{n-1} (\nu_{i-1} - \nu_i) g_i \right] \\ &\leq \frac{M - m}{2} \sum_{i=0}^{n-1} \nu_i h_i, \end{aligned}$$

where  $h_i = x_{i+1} - x_i$ .

*Proof.* Applying inequality (3.13) of Corollary 1 on the interval  $[x_i, x_{i+1}]$  for  $i = 0, 1, \dots, n-1$  we have

$$\begin{aligned} &\left| \int_{x_i}^{x_{i+1}} w(x) f(x) dx - \frac{\nu_i}{2} [f(x_i) + f(x_{i+1})] \right. \\ &\quad \left. - \frac{m}{2} [x_{i+1}^2 - x_i^2 - (x_{i+1} + x_i) \nu_i] \right| \\ &\leq \frac{\nu_i}{2} [f(x_{i+1}) - f(x_i) - m(x_{i+1} - x_i)]. \end{aligned}$$

Summing over  $i$  for  $i = 0, 1, \dots, n-1$  gives the quadrature rule

$$\begin{aligned} A(w, f, I_n) &= \frac{1}{2} \sum_{i=0}^{n-1} \nu_i [f(x_i) + f(x_{i+1}) - m(x_i + x_{i+1}) + m(x_{i+1}^2 - x_i^2)] \\ &= \frac{1}{2} \sum_{i=0}^{n-1} \nu_i [f(x_i) + f(x_{i+1}) - m(x_i + x_{i+1})] + \frac{m}{2} (b^2 - a^2) \\ &= \frac{1}{2} \sum_{i=0}^{n-1} \nu_i \frac{1}{2} (g_i + g_{i+1}) + \frac{m}{2} (b^2 - a^2) \end{aligned}$$

where  $g_i = f(x_i) - mx_i$ .

Hence

$$A(w, f, I_n) = \frac{1}{2} \left[ \nu_0 g_0 + \nu_{n-1} g_n + \sum_{i=1}^{n-1} (\nu_{i-1} + \nu_i) g_i \right] + \frac{m}{2} (b^2 - a^2).$$

The remainder term  $R(w, f, I_n)$  is such that

$$\begin{aligned} |R(w, f, I_n)| &\leq \frac{1}{2} \sum_{i=0}^{n-1} \nu_i [f(x_{i+1}) - f(x_i) - m(x_{i+1} - x_i)] \\ &= \frac{1}{2} \sum_{i=0}^{n-1} \nu_i [g_{i+1} - g_i] \\ &= \frac{1}{2} \left[ \nu_{n-1} g_n - \nu_0 g_0 + \sum_{i=1}^{n-1} (\nu_{i-1} - \nu_i) g_i \right]. \end{aligned}$$

Using the second inequality in Corollary 1 gives

$$|R(w, f, I_n)| \leq \frac{M - m}{2} \sum_{i=0}^{n-1} \nu_i h_i.$$

Hence, the theorem is proved. ■

If a uniform grid is taken so that  $x_i = x_0 + ih, i = 0, 1, \dots, n$ , then

$$|R(w, f, I_n)| \leq \frac{M - m}{2} \cdot h \cdot \nu.$$

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